Reinterpretation of the Dougong joint by the use of parametric tools and robotic fabrication techniques

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Traditionally, Chinese architecture was based on the use of timber frameworks as structural system. The Dougong joint is amongst the typical connection typologies, widely applied in the timber heritage buildings in China. Each component of the Dougong (bucket-arch joint) conforms to a strict structural proportion in addition to simple but efficient connection methods between its different components. However, the spread of the structure in modern architecture is limited due to high labour cost. Parametric design and digital fabrication techniques have greatly promoted the development of complex timber structures in recent years, which could be introduced in order to reinterpret the Dougong joint. In continuation of our research on exploring the application of robotic technologies for the fabrication of traditional Chinese timber joints, our paper will investigate the feasibility of the structural logic of the Dougong and how it could be applied in a modern timber framework structure.

Keywords: *Dougong joint, timber structures, parametric design, robotic fabrication, optimization algorithm, topology optimization*

INTRODUCTION

The introduction of the Dougong joint

The Dougong (bucket-arch), also known as Kegong, Douke, Zantiao, Puzuo, etc, is a key structural element of traditional Chinese architecture (Ma, 2003). Located between the top of the column and the crossbeam transfers the load of the building's eaves to the column. Besides China, the bucket arch is a key component of the East Asian wood frame building structure (Yuan et al., 2011). The emergence and development of the Dougong joint had a very long history. Being one of the prominent features of traditional Chinese timber frame architecture, the Dougong was widely used during the Han Dynasty, 202 BC - 220 AD, (Dehua, 2011). The Dou is a bucket-shaped wooden block, and the Gong is a bow-shaped short piece of wood. The Gong is placed on top of the Dou, protruding outwards, and the Dou is placed on the end of the Gong, thus it is criss-crossed layer by layer, forming a structure with a big upper and a smaller one (Figure 1), (Dehua, 2011).

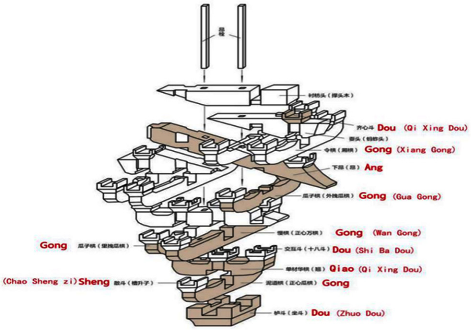


Figure 1
The structure of the Dougong

The use of Dougong in the ancient Chinese buildings

The Dougong has four main functions: load transfer, extending the end of the roof overhang, earthquake resistance and decoration. The Dougong is located between the column and the beam (Figure 2), (Dehua 2011). The load from the roof and the upper frame is transmitted to the column through the Dougong, and then from the column to the foundation. It also transfers the load of the roof overhang ending to the pillar, thus extends its length. The Dougong plays a role in earthquake resistance as well (Yuan et al. 2011). Its elements are connected to each other by mortise and tenon joints, which releases the energy transmitted to the building by an earthquake and greatly reduce the seismic load of the entire house (Wu, Song, and Li 2018). Due to its aesthetics and exquisite structure, it is amongst the most characteristic decorative elements of traditional Chinese architecture.

Research aims

An inexperienced craftsman will need a long time to train his skills before becoming experienced, which would be required for the construction of the Dougong as it is the most complex wooden tectonic detail in traditional Chinese buildings. There are even explicitly trained craftsmen named 'Dougong carpenters' explicitly trained for this purpose (Ma, 2003). But if the proportions and size of the timber tectonics are stored in the form of the parametric model and CNC/robotic technologies could be applied to produce the structural elements based on that data, even an inexperienced craftsman could quickly produce the corresponding structural components (Willmann et al., 2016). A parametrized, robotic system could potentially not only save time significantly but also transfer traditional design knowledge to contemporary design solutions, which would enable the fully automated production of complex timber components (Willmann et al. 2016). Based on the above hypothesis our paper will answer the following questions:

1. What is the structural logic of the Dougong?
2. How can we utilise Dougong's structural logic by using parametric tools, and apply it in modern architectural solutions by using robotic tools?

To answer these questions, we will first analyse different case studies which have introduced methods of how to utilise traditional timber structures into modern architecture by using parametric tools and robotic fabrication techniques. We will then propose a computational design and fabrication framework that will integrate topology optimization, a genetic algorithm and robotic fabrication after analysing the underlying principles of the Dougong set. In this paper, we will mainly focus on the feasibility of the structural logic of the Dougong using parametric tools.

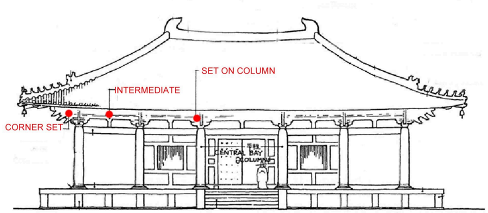


Figure 2
The locations of the Dougong joints on a traditional Chinese building

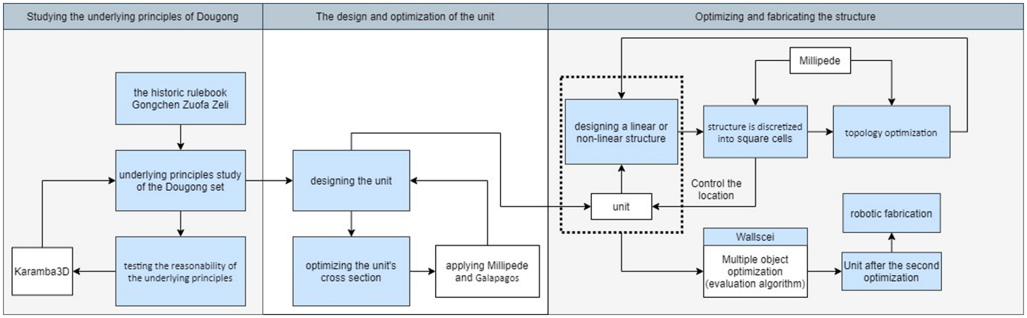


Figure 3
The design to fabrication framework

MATERIALS AND METHODS

Literature review

We will conduct a comparative analysis of three different cases studies, two of which have analyzed the structural logic of timber tectonics of traditional Chinese architecture and applied it in contemporary designs, while the third case introduces the voxelization, topology optimization and stress analysis of timber tectonics.

At the University of Tongji, the research team of Philip Yuan explores the possibility of the application of a traditional Chinese eaves rafter in modern architecture by fabricating an umbrella-shaped, modular installation with a 5 axis CNC router (Yuan and Hua, 2019). They developed a workflow, including the prototype research of the eaves rafter, the simulation and optimization of structural performance, and digital fabrication. Through simulation, analysis, and comparison of the bending moments of the eaves rafter under three kind of overhanging ratios, the researchers find out that the original ratio is reasonable which is the underlying principle of the eaves rafter. They developed a new modular unit and applied it to designed the umbrella structure based on the principle that a support point divides the eaves rafter into two parts while the proportion between the two parts maintained at 0.46-0.48. Before fabricating the umbrella structure, the cross-section of the unit was optimized using the Millipede plug-in for Rhino/-Grasshopper, which helped to reduce the structure's weight. The fabrication process included the introduction of a 5-axis CNC router. Their methodology provides a good insight into the field of reinterpretation of traditional timber tectonics. The wood element is produced with robotics, but they fabricated the structure manually rather than applying robotics in the process of assembly.

At the University of Hong Kong, Lange (2017) organized a fabrication-studio to explore how to reinterpret three kinds of traditional Chinese tectonics such as the Dougong, a reciprocal structure found in woven, timber arch bridges in China, and the Chidori system by using Rhino/Grasshopper and a 5-axis ABB industrial robot. The students analyzed the connection methods of the three modular timber systems firstly and designed new modular units based on the analysis result. The 5-axis ABB industrial robot used a spindle and a milling end-effector in order to produce the new units. Their research provides a good insight into the process of robotic fabrication of the re-invention of traditional modular units. However, the researchers did not explain the underlying principles of the three material systems in a systematic way and did not try to optimize the size of the new structures.

Naboni and Kinics's (2019) developed an optimized bridge consisting of modular timber units. They explored a new design and robotic assembly method including techniques such as topology optimization, voxelization, and robotic fabrication. After designing the bridge out of a modular unit, they applied 'Millipede' to analyse the stress lines of the bridge's structure. After that, the structure is subdivided into square boxes for making sure each stress line is applied to each box. Each unit is following the orientation of the stress line inside of the box. The new bridge design is lighter than the original one, despite having the same mechanical properties as the previous bridge. Two UR10 robots were used to produce the units and assemble the structure following the coordinates of the boxes. Their method provides a useful reference for our research. However, the researchers do not take into consideration further aspects such as the design method and size optimization of the unit.

Methodology

Having analysed these case studies, our research introduces a new methodology that includes three main phases (Figure 3), which are: the study of the underlying principles of the Dougong, the design and optimization of the unit, and the optimization of the structure and the robotic production of the unit. The paper will continue our previous research (Zhao et al., 2020) to analyse the proportion of the Dougong elements and will present a new conceptual method of optimizing a small timber footbridge.

The first phase is about understanding the underlying principles of the Dougong joint by studying and analyzing the historic rulebook Gongchen Zuofa Zeli recording the size, the technology, and the structure of different kinds of Dougong joints. In this phase, the size and proportions of the Dougong elements are being defined and the reasonability of the ratio of the distance between each adjacent force point of the components of the Dougong are being tested through simulation in 'Karamba3D' (Preisinger, 2013), a plug-in for structural analysis in Grasshopper.

The second phase is about designing and optimizing the principal unit based on the mechanical rules of the Doungong joint in the Rhino/Grasshopper environment. In this phase, 'Millipede', a plug-in for topology optimisation and 'Galapagos' a plug-in for genetive algorithms were used to analyze and optimize the cross-section of the unit as described in our previous paper (Zhao et al., 2020).

In the third phase, we developed a computational workflow aiming to simplify the process of applying the unit for the design of architectural solutions such as a wall, a bridge or a pillar. In our workflow, topology optimization, voxelization, multi-objective optimization, and robotic fabrication are integrated with design, analysis and structural optimization in a Rhino/Grasshopper environment. The research will explore the feasibility of the workflow by verifying it on a linear and a non-linear structure. A wooden bridge has been chosen as the design object on which our computational framework will be applied.

Phase one: Analysing the underlying rules of Dougong. Through studying and analyzing the historic rulebook Gongchen Zuofa Zeli, the proportion rules and the connection methods of different kinds of Dougong joints were revealed. Each Dougong element is equally divided into 2*n parts [n>0, $n \in N$(integer), one part=3 Dou] according

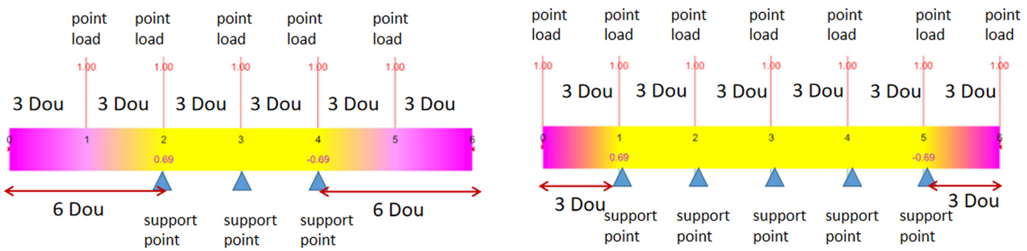
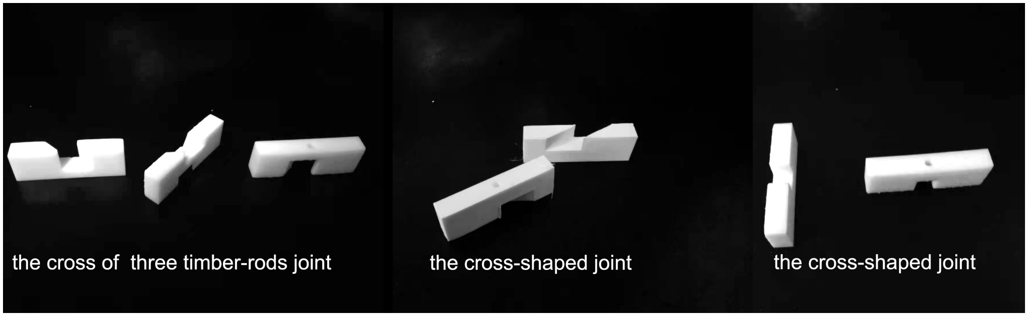


Figure 4
Option A: both sides of the element extending 2 parts outwards from the support point of the edge (left), Option B: both sides extending 1 part (right)

Figure 5
The Dougong connection methods



to the distances between two adjacent load and support points. Both sides are either extending two parts or one part outwards from the support point of the edge (Figure 4). There are three kinds of angels between two elements, such as 120°, 135° and 90°(Ma, 2003). The connection of the different elements in the same layer takes place by the crossing of three straight timber joints or a cross-shaped joint (Figure 5). The connection of the elements in the different layers takes place by using straight tenons. According to the studies of Ma (2003) and Liang (2006), the size of the cross-section of most of the elements in the Dougong is set as 1 Dou in width and 2 Dou in height or 1.25 Dou in width and 2 Dou in height. The ratio of height to width equals 1:2 approximately. Therefore, we set the unit's preoptimization size to 1 Dou in width and 2 in Dou height. There are eleven classes in the Doukou system, the width of the first-class Dou is 19.2 cm, thus the width of one Doukou is 19.2cm. Each class is linked to a particular building function and any change from class to class is based on the formula described by Zhao et al. (2020):

1 Dou = 19.2cm + (1- X) * 0.5 Cun, (1Cun=3.33cm), X: the class of Cai (1, 2, 3, 4, ..., 11);Cun is the traditional unit of length in China

An element of Dougong is chosen as an object to test the feasibility of the traditional proportion rules by using 'Karamba3D'. We choose the first-class Cai (1 Dou=19.2cm) as the standard unit. The dimensions of the element are 19.2cm in width, 24cm in height and 22.5cm in length, which can be considered as a beam to tested. Options A and B are both tested in 'Karamba3D'. In the simulation, the figuration of the displacement plays an important role to evaluate the fitness of the structure. According to the stiffness calculation,κ=F/σ (κ: the stiffness, F: the force on the body, σ: the displacement), a smaller displacement means that the structure is more stable with the given forces.

For option A we assume that the element is subjected to point loads of 1 kN. When A: B: C: D: E: F equals 1: 1: 1: 1: 1: 1, the displacement of the element is 0.002491cm. When A: B: C: D: E: F equals 3: 4: 2: 2: 4: 3, the displacement of the structure is 0.005011cm. The displacement of the latter is larger than the former, which means the stiffness of the element has been reduced. Thus, the stiffness will be reduced when the length of the overhanging structure is increased. When A: B: C: D: E: F equals 3: 1: 5: 5: 1: 3, the displacement of the element is 0.00206cm (Figure 6). The displacement of the structure is smaller than the original structure. However, the length of the overhanging part is reduced. In summary, when the proportion of the distance between the original structure's stress points is 1:1:1:1:1:1, the structure is reasonable relative.

In option B, the displacement of the element is 0.001003cm, 0.005011cm and 0.00206 cm, when the proportion of the distance between the load points is 1: 1: 1: 1: 1: 1, 4:2:3:3:2:4 and 1:5:3:3:5:1 respectively. When A': B': C': D': E': F' equals 4: 2: 3: 3: 2: 4, the displacement of the element is larger than the

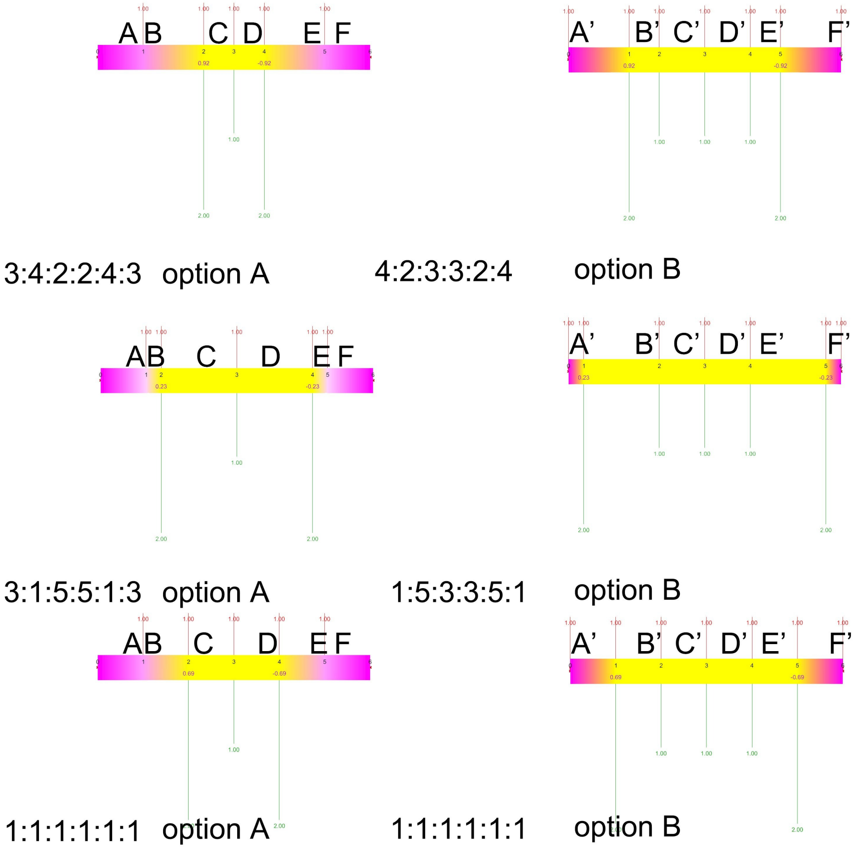


Figure 6
The simulation-results of option A, where both sides of the element are extending 2 parts outwards from the support point of the edge (left), and version B, where both sides extending 1 part (right)

original proportion, which means that the fitness is not better than the original element of the Dougong (Figure 6). At the same time, when the proportions are 1:5:3:3:5:1, the displacement is smaller than the element (1:1:1:1:1:1), but both sides outwards of the structure are reduced compared with the element (1:1:1:1:1:1). After a comprehensive comparison, the original force ratio is the most reasonable.

Phase two: the design and optimization of the unit. We have explored strategies to simplify the Dougong elements for making them more suitable for modern architecture in our previous paper (Zhao et al., 2020). We simplified two elements of the Dougong by adjusting their dimensions to integers and removed the decorative elements and their complex curves (Figure 7). At the same time, we have designed two units based on the mechanical properties and proportions of the Dougong and explored assembly possibilities following the connecting rules as presented by Zhao et al. (2020). After that, the cross-section of the units was optimized with Millipede and Galapagos.

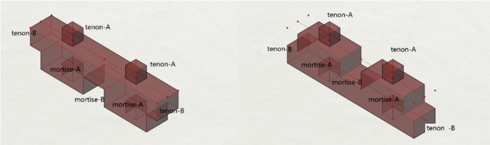


Figure 7
The new simplified elements of the reinvented Dougong unit

Phase three: the optimization of a wooden arched footbridge. A small arched footbridge was chosen as an object to evaluate our proposed method of optimization and robotic fabrication (Figure 8). Firstly, the arch structure is discretized into square cells, the size of which is set by us. In the process of optimization, the topology optimization algorithm calculates which cells should be deleted, based on the utilization rate within the structural system according to a given set of loads, boundary conditions, and constraints. Topology optimization is a mathematical method for structural optimization of material layout within a given area according to a given set of loads, constraint conditions and performance indicators (Bendsoe and Sigmund, 2013). Taking material layout as the optimization object, through topology optimization, the algorithm can calculate the most reasonable material layout of the design space (Bendsoe and Sigmund, 2013). Secondly, a square cell was set as a boundary to control the position of the units within the bridge arch. Thirdly, the weight of the arch structure was reduced by optimizing the cross-section of the unit by using Wallacei, a plug-in for evolutionary algorithms in Grasshopper. After the optimization, the tool path of the robotic assembly of the units was generated automatically based on the parametric model of the unit within the visual programming environment. We have adjusted the robotic assembly tool path based on the fabrication simulation in RoboDK, a firmware for industrial robots and offline programming. During the whole process, the data of each phase was delivering timely feedback to all other phases and ensured that the architect can control the whole design and manufacturing process.

CONCLUSION

Our research has revealed and verified the underlying principles of the Dougong by analyzing the original materials and simulating them in Karamba3D. A moderately sized component, width 1 Dou in height, 1.25 Dou in width and 18 Dou in length, was chosen as the object to analyze the feasibility of the Dougong element's proportions. We have tested two rules, option A and B. In the simulation option A, where A: B: C: D: E: F equals 3: 4: 2: 2: 4: 3, the displacement was larger than in the original Dougong element, which means that the stiffness of the element is smaller than the original one. The displacement is smaller than the original ratio when A: B: C: D: E: F equals 3: 1: 5: 5: 1: 3, but both sides of the element extend outwards reduced in comparison to the original element of the Dougong. This weakens the properties of the Dougong because one function of it is to extend the overhang. In the situation of option B with the same constraints, when A': B': C': D': E': F' equals 3: 4: 2: 2: 4: 3 or 3:1:5:5:1:3, the displacement is larger or smaller than the one (1:1:1:1:1:1). However, this doesn't appear reasonable compared to the original proportion (1: 1: 1: 1: 1: 1), because of the same reasons observed in the simulation of option A. The results of the simulation show that the ratio of 1:1:1... :1 is the optimal standard.

The paper also explored a new method of optimization and robotic fabrication of a timber arched footbridge by analyzing and optimizing it within a given set of loads. The weight of the wooden bridge was reduced from 16.592 kg to 2.954 kg after the optimization with Millipede and Wallacei, due to its transformation from a solid structure to a frame structure being able to carry the same loads. This proves that our method could be useful in the field of optimization and robotic fabrication, which should be explored further in future work.

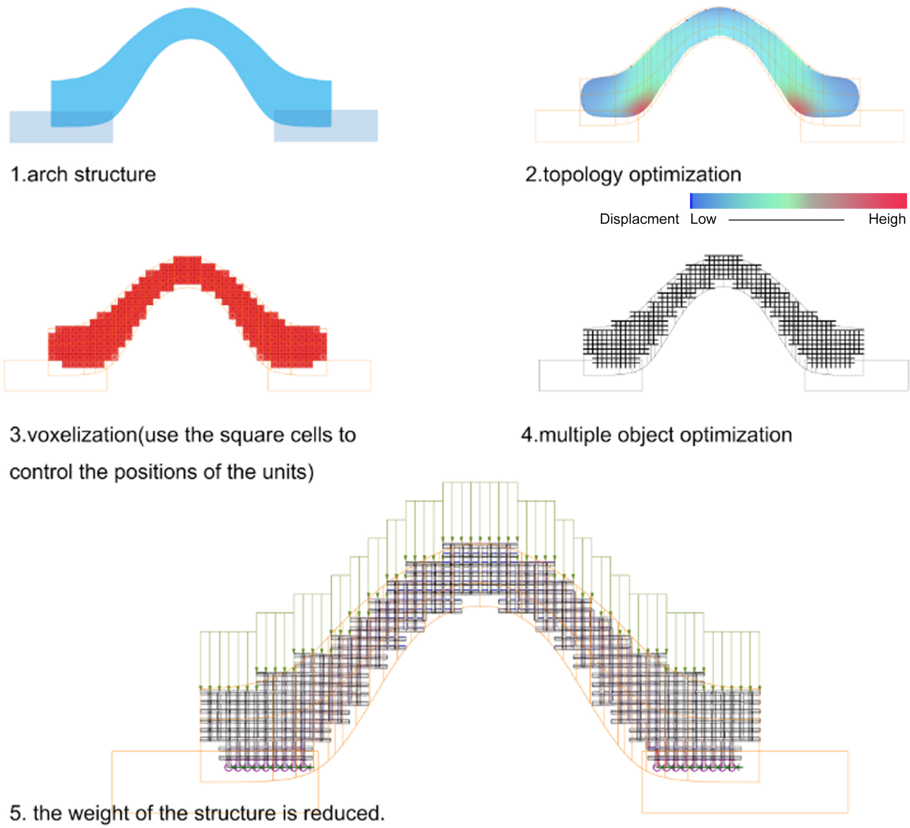


Figure 8
The topology optimization process of the footbridge.

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